ADVANCES IN FOREST SOIL ANALYSIS

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Abstract.--Advances and deficiencies in current knowledge of forest soils are described under the following headings: soil chemical characteristics, laboratory instrumentation and analytical chemistry techniques; soil physical characteristics, soil classification, and soil microbial characteristics. Relevant examples are given under each subheading, and directions for future research are discussed.

Additional keywords: Analytical techniques, instrumentation, soil classification, soil chemistry, soil microbiology, soil physics.

This paper sketches some advances in a variety of analytical procedures and approaches over the last 5 years or so in the broad research area of "forest soils". The review is not meant to be complete; the literature cited is given only to exemplify relevant studies. Potential avenues for future research are also identified.

I. SOIL CHEMICAL CHARACTERISTICS

A continuing problem is the choice of extraction techniques that yield analytical determinations that can be used as indices of availability to plants, and perhaps, to predict tree growth.

1. Cation exchange capacity and exchangeable cations

Cation exchange capacity (CEC) is the sum of exchangeable cations that a soil can absorb. It is usually expressed in milliequivalents per 100 grams of soil, although under the new international system, "Le Systeme International d'Unites" (SI system) which is now widely adopted, the unit is mole per kilogram (Thien and Oster, 1981).

The most common method of extraction is with NH_4OAc at pH 7.0. The leaching device of Holmgren et al. (1977) enables strict control of rates of extraction. Using NH_4OAc at pH 7.0, provides a measure for soils having pH values near 7.0. However, most forest soils have lower pH values of 3.5 to 6.5 and have high organic matter contents in upper horizons. Thus, determination of CEC at pH 7.0 yields an inflated measure for most acid forest soils. Because CEC is often used to characterize the "fertility" of forest soils, may be used to estimate fertilizer retention, and may be used to assess the relative sensitivity

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of soil to "acid rain," etc., it is important to have realistic estimates of CEC. Thus, soil extraction should be made at a pH applicable to field conditions.

Most of the negative charge of the CEC in forest soils high in organic matter is contributed by the humus fraction and only secondarily by the clay fraction. For example, in A-horizons of over 30 forest and range soils of California, 1% of organic carbon contributed about 15 times more to the CEC than did 1% of clay (author's unpublished data).

An insignificant negative charge is contributed to the CEC by hydrous oxides; these oxides may even be positively charged at low pH. The charge of the clays arises from isomorphous replacement, ionization of OH groups on clay edges, and pH-dependent charges associated with Al oxides. Organic matter has negative charges primarily from ionization of COOH groups and to a lesser extent from phenolic OH and NH groups. Nearly all of the CEC of highly organic soils such as peats, as well as humus layers of forest soils, is due to organic matter. In fact, about 25 to 90% of the total CEC of the upper horizons of mineral soils is generally caused by organic matter (Stevenson, 1982), and the charge characteristics of organic matter are highly dependent on the pH. Thus, for soils high in organic matter, the determination of CEC is particularly troublesome. Data of Helling et al. (1964), of 60 forest and grassland soils in Wisconsin, clearly illustrate the problem (Table 1). For soils with mean organic matter and clay contents of 3.3% and 13.3% respectively, the mean relative contribution of organic matter of total soil CEC varied from 19% at pH 2.5 to 45% at pH 8.0

Table 1.--Changes in CEC of organic matter and clay with pH of saturating extract solution. Data of 60 Wisconsin soils. (From Helling et al., 1964)

pH	Average CEC: Organic matter	Average CEC: Clay
	----------meq/100 g----------	
2.5	36	38
3.5	73	46
5.0	127	54
6.0	131	56
7.0	163	60
8.0	213	64

Similarly, Kalisz and Stone (1980) studied the changes in CEC with pH of acid forest humus layers and mineral soils (Table 2). Organic matter was the main source of exchange capacity at all locations studied. They found that CEC's measured at the pH of air-dried samples using an unbuffered salt procedure were 1/4 to 1/2 those measured by NH_4OAc extraction at pH 7.0, and thus effective base-saturation was two to four times greater at the natural field pH of the soil rather than at pH 7.0. Their data (Table 2) show that an H-layer with pH below 4.0 can have 15-30% of its effective charge countered by

Table 2--Effect and base-saturation by determination of CEC at field pH versus CEC at pH 7.0, for mors from the Adirondacks, and for mulls from McGowan's Woods, New York. (From Kalisz and Stone, 1980).

pH	Organic matter (Percent)	Base-saturation of CEC at: Field pH	pH 7.0
		-------Percent--------	
	H layers of mors:		
3.3	50	15	4
3.4	66	29	8
3.5	91	21	5
4.1	75	8	2
4.9	39	32	14
	Mineral horizons of mulls:		
4.9	6	58	21
5.0	12	63	25
5.2	1	51	10
5.4	3	81	23
5.4	5	94	41

bases, and that a mull at pH 5.4 can have an apparent base saturation of 81-94%. These high values for mulls at their field pH are quite comparable to effective base saturations of other soils, including productive agricultural soil (e.g. Coleman et al., 1959; Pratt and Blair, 1962). Kalisz and Stone (1980) point out that the reduced CEC measured at field pH, and the wide range of total exchange capacity noted in their study, have obvious bearing on the retention of recycled bases and cations added as fertilizers. Acidification and reduction of nutrient bases due to leaching by acid atmospheric precipitation will also be influenced by base-saturation and the total quantity of bases in organic matter. Thus, careful attention must be given to the large contribution to the CEC by organic matter, as there are practical needs for correct measurement of effective exchange capacity. Perhaps the example of Kalisz and Stone (1980) of measuring CEC at the field pH of the soil, or a method utilizing an unbuffered electrolyte extraction (Grove et al., 1982), should be followed.

Are there methods of determining the CEC and extractable nutrients that yield results correlated with tree growth? There are no clear, universal answers to this rhetorical question, because of the variety of factors that control productivity. If the rate-limiting step of nutrient uptake is the exchange of nutrient ions from the soil to the soil solution, then identification of the best way of determining CEC and exchangeable soil cations might be clearer, but it is extremely difficult to generalize about such a rate-limiting step. For example, Fried and Broeshart (1967) proposed that the active accumulation of ions in roots is the rate-limiting step of uptake under steady-state conditions for most ions. On the other hand, the critical review

by Nye (1977) indicates that the diffusion rate of ions in the soil is probably the rate-limiting step in the growth-response range of soil-nutrient concentrations.

Adams and Boyle (1982) distinguished between total and exchangeable cation composition of some Michigan Spodosols. They concluded that, although significant bound reserves are present, the exchangeable nutrient pools probably provide most of the cations necessary for growth. The problem is to choose the best method for the estimation of the exchangeable pool.

Klinka et al. (1980) compared the NH_4OAc, pH 7.0 extraction method with three other extraction methods, with respect to their ability to yield cation amounts closely correlated with tree productivity in coastal British Columbia. They determined extractable K, Mg and Ca in 42 forest soils in the coastal western hemlock zone, comparing the following extractants: NH_4OAc, pH 7.0; NaOAc, pH 4.8; 10% HCl and 1% citric acid. The individual cation quantities determined were poorly correlated with forest productivity, regardless of the extraction method used. This result was not unexpected, for as the authors pointed out, there are many physical, chemical and biological factors which contribute to productivity. Of the methods tested, though, the NaOAc, pH 4.8 method yielded values of exchangeable cations most closely correlated with productivity. The average field pH's of the soil tested were closer to that of the best extraction solution (pH 4.8) than to pH 7.0 of the NH_4OAc extraction solution normally used. Mean pH values ($\pm$standard deviations) for the 42 soils tested by Klinka et al. (1980) were: 4.1 ± 0.5 for the LFH horizon, 4.2 ± 0.7 for the A-horizon and 4.9 ± 0.4 for the B-horizon.

Recent recommendations of the Soil Science Society of America recognize the desirability of determination at the field pH. Gillman's (1979) procedure is recommended for acid soils and those with variably-charged matrices (Rhoades, 1982). In this method the soil is saturated with Ba and then equilibrated with $BaCl_2$ with a solution concentration equivalent in ionic strength to the soil solution. The soil is then reacted with $MgSO_4$ (adjusted to a comparable ionic strength of the soil solution) to replace Ba with Mg. The use of unbuffered solutions throughout ensures that natural soil pH is not significantly altered. Magnesium concentration in the supernatant is then determined (e.g., by atomic absorption spectrometry). The CEC is equivalent to the Mg adsorbed.

Many foresters, especially those managing tree nurseries, require CEC determinations, but CEC determinations are not commonly done by many soil testing laboratories. Thus, Grove et al. (1982) recommends the sum-of-cation calculation method (ΣAl, Na, K, Mg, Ca), using an unbuffered electrolyte extraction for Al, for soil testing that will yield the most unambiguous information of CEC and the acidity associated with the exchange sites, under field conditions.

2. Extraction and analysis of other elements

The recent literature also contains numerous studies of different extraction techniques, including those for sulfur, phosphorus, nitrogen and aluminum. Most of the procedures used for estimating available soil S, P and N are based on arbitrary analytical methods, with no general agreement on a best index of availability to plants. A brief but excellent discussion and detailed methods for sulfur are given by Tabatabai (1982). Forest soil scientists will be

particularly concerned about N, S and Al determinations because of implications of the acid rain problem.

Perhaps we should focus on those methods for nitrogen and sulfur that closely parallel estimates of microbial activity because the rate-limiting steps determining availability are likely to be microbially mediated. The soil incubation techniques conducted under field conditions are most promising for nitrogen (e.g. Powers, 1980; Edmonds and McColl, 1983). Less emphasis has been placed on similar incubation techniques for sulfur, but such methods (e.g. Kowalenko and Lowe, 1975a,b) should be looked at closely.

Analyses of the trace elements (Fe, Mn, Zn, Ni, Cu, and Cd) in soil are best carried out using the relatively new DTPA (diethylenetriaminepentaacetic acid) extraction technique, first reported by Lindsay and Norvell (1978). These elements are of interest to forest-soil scientists in situations where sewage sludges and other waste products containing trace elements are added to forest soils, in tree-nurseries where heavy fertilizer use may result in trace-element problems, and where "acid rain" may mobilize trace elements in soil.

II. INSTRUMENTATION AND ANALYTICAL CHEMISTRY TECHNIQUES

1. Flow injection analysis

Sensitivity and speed of analysis have been greatly enhanced by automated procedures based on the principles of "continuous flow analysis." The concentration of analyte is measured in an uninterrupted stream of liquid; successive samples are passed along the same path in the instrument with reagents being added and mixed while the samples move toward a flow-through cuvette where monitoring is made and recorded automatically. Instrumentation of this type is essential for analysis in most forest-soil research where large numbers of samples are required.

The first continuous-flow system was used for the determination of urea and glucose in blood about 30 years ago, the Technicon Auto-Analyzer being the most popular instrument. One great difficulty, though, is the mixing of adjacent samples in the flow-line. The most common method to minimize sample intermixing is to introduce air bubbles, thus dividing the flowing stream of samples into separate compartments of fluid.

There is now a simpler, more sensitive, faster, and cheaper method devised for automated chemical analyses of fluid samples requiring less volume of sample than in previous air-segmented techniques. The method is called "Flow Injection Analysis" (F.I.A.), and is based on the injection of liquid samples into a moving, nonsegmented, continuous-carrier stream of liquid. As Ruzicka and Hansen (1981) point out, these two features result in higher sampling rates with small sample-volumes and very rapid availability of the analytical readout. The controlled dispersion of the sample zone, which is new in analytical chemistry, allows design of a FIA system exactly suited to automate a given analytical procedure, including those for determination of NO_2^-, NO_3^-, NH_4^+, and PO_4^{3-}, to name a few.

2. Voltammetry, polarography and stripping voltammetry

These techniques would be most useful for analysis of heavy metals in forest soil or soil solution in situations where, using older methods, interferences by high salt concentrations may cause analytical problems, e.g. following application of sewage sludge or fertilizer salts.

In voltammetry, the current applied to an electrode is measured as a function of potential, or voltage; if a dropping mercury electrode is used, the process is called polarography (Street and Peterson, 1982). Polarography is particularly suited for the analysis of trace inorganic elements in soil, water, and sediment, generally without prior chemical separation and over a very wide range of concentration.

Stripping voltammetry is a two-step technique (Street and Peterson, 1982). The first step is the electrolytic deposition of a chemical species onto an inert electrode surface at a constant potential, and the second step involves a voltage scan of the electrode, causing a dissolution (stripping) of the various species in the amalgam formed on the electrode, back into solution at characteristic potentials. It is primarily a trace analytical technique from the sub-parts per million level to about 10 ppm.

3. High-pressure liquid chromatography (HPLC)

There is renewed interest in the organic fraction of forest soils, e.g. because of the problems related to effects of "acid rain," and the apparent increase in mobility of aluminum (and other toxic elements) in organo-complex forms, and because of problems arising from disturbance of soil organic matter by various forest management practices.

HPLC is a highly versatile, rapid, and basically non-destructive method for identifying a wide variety of volatile and non-volatile organic compounds (Hasset, 1982). The conditions used are mild, involving ordinary solvents from hexane to water, and ambient temperature. The high versatility of HPLC is due to the large number of columns available for separation, and the many types of detectors for individual compounds, e.g., ultraviolet/visible fluorescence, electrochemical, refractive index, and conductivity.

III. SOIL PHYSICAL CHARACTERISTICS

1. Soil disturbance and compaction

Disturbance of surface soil by various forest management practices is a major problem affecting growth of trees in the next rotation (McColl and Powers, 1984). Such disturbance includes removal of litter and a portion of the A-horizon, as well as soil compaction with or without removal of material. Problems generally arise when wet, loose soils are compacted, and when organic matter is removed.

There have been recent advances in our knowledge of these problems both in North America and elsewhere, exemplified by the review on compaction of forest soils (Graecen and Sands, 1980). Sands and Bowen (1978) and Sands, Greacen and Gerard (1979), document increased compaction in sandy soils of South Australia that correlate with decreased productivity of radiata pine plantations, but this is not to imply a simple cause-and-effect relationship; other factors, such as nitrogen deficiency, are also involved.

It is difficult to establish exactly how soil disturbance affects tree establishment and productivity, because the factors involved are many, interrelated, and often site-specific. In addition, there is often confusion in the literature regarding "compaction" and "density"; the difference between these is not always distinguished. The common way to characterize compaction is by bulk density measurements, but bulk density itself is not a measure of compaction. Higher bulk density of the surface of a managed soil does not necessarily mean that the surface soil has been compacted; it may simply be a consequence of the removal of less-dense surface material.

Froehlich (1983) compiled data from several field studies, showing that reductions in seedling growth are correlated with proportionate increases in soil density (Fig. 1). Data of Sands (1983) in Fig. 2 show differences in soil strength profiles between adjacent land-uses on the same soil, which presumably reflect differences in degree of site disturbance. The soils under native Eucalyptus forest are least compacted and under planted radiata pine are most compacted, and soils under second rotation pines are often more compact than under first rotation pines. Sands (1983) emphasized that the most important single factor in the long-term productivity of the sandy soils he studied is maintenance of soil organic matter. No management practice that reduces the amount of soil organic matter or restricts its distribution with depth should be considered, even at the expense of short-term gains.

More research is needed to identify the causal factors of decreased forest productivity following harvest operations, and to understand the mechanisms involved. Once a clearer picture emerges, prescriptions for correction can then be made more intelligently than in the past.

2. Soil reinforcement by tree roots

The role of trees in maintaining slope stability has heen debated for some time (e.g., Endo and Tsuruta, 1969). Gray (1970) pointed out that the root system provides mechanical reinforcement to the soil, vegetation adds a vertical slope surcharge, trees moved by wind increase the potential for surface shears, and the soil-water balance is altered by transpiration. There is clear evidence that tree removal results in increased levels of soil moisture (e.g. McColl, 1977; Rogerson, 1976). However, Waldron (1977) indicated that the effect of plant roots increasing soil shearing-resistance by mechanical reinforcing could be more important than water removal by transpiration, because landslides occur most often during rainy periods when matric potentials may rise to zero or above, irrespective of vegetation.

Recent significant studies made on soil reinforcement by tree roots include that by Waldron, Dakessian and Nemson (1983). They simulated natural conditions by using 1.22 x 1.22 m cylindrical soil containers in which artificial soil profiles were planted with alfalfa and ponderosa pine; controls were unplanted. A large pneumatic device sheared both root-free and root-permeated soil along a horizontal plane at the 0.6 m depth. The pine roots clearly enhanced soil strength more than alfalfa roots did, and at displacements ≥ 25 mm, values of ΔS and S_r/S_f were greater for pine (Table 3). In addition, S continued to rise over the shear displacement range in pine-rooted soil, whereas with alfalfa-rooted soil S did not increase appreciably after 25 mm shear displacement. The superiority of pine roots in increasing soil shear strength was in accord with field observations that woody plants are more effective

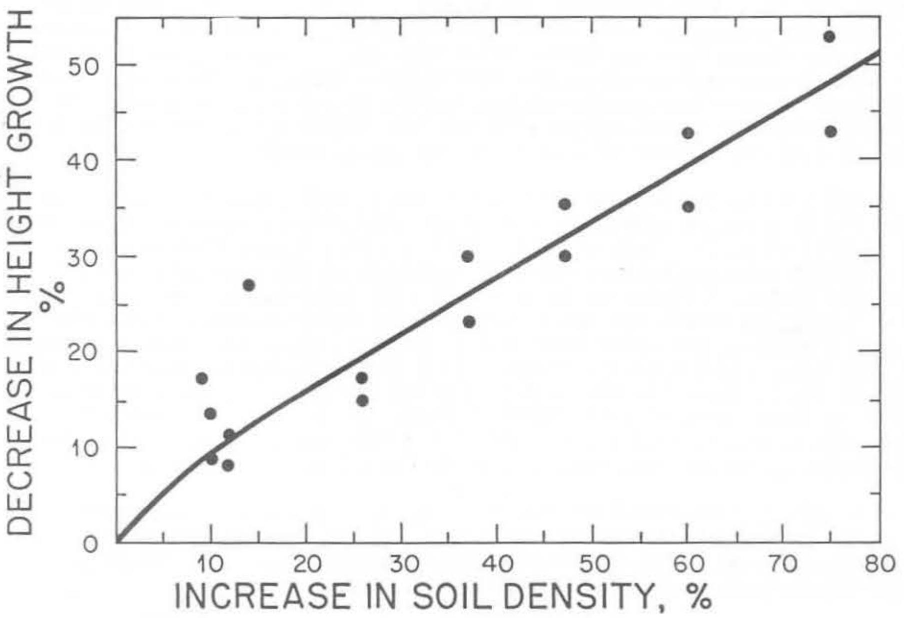

Figure 1.--Tree growth affected by soil density (from Froehlich, 1983).

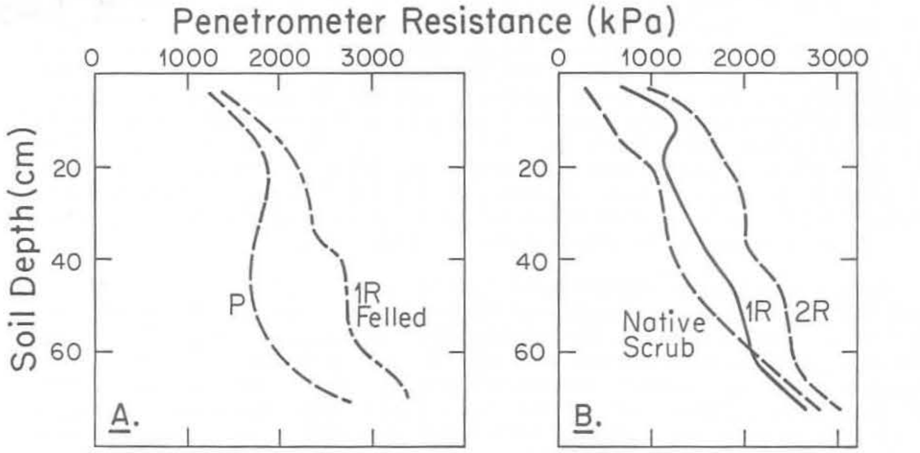

Figure 2.--Changes in penetrometer resistance with soil depth for different land use adjacent on the same soil type: (a) P = pasture, IR-felled = after felling first rotation 49-year-old radiata pine; (b) Native scrub = native Eucalyptus baxteri and E. huberiana forest, 1R = first rotation 70-year-old radiata pine, 2R = second rotation 12-year-old radiata pine following first rotation 46-year-old pine (from Sands, 1983).

Table 3.--Comparison of shear stress for soil with 54 month-old pine, soil with 11 month-old alfalfa, and fallow soil with no plant roots (from Waldron et al., 1983).

	Shear stress (S) at 25 and 50 mm shear displacements. S(25)	S(50)
	-----kPa-----	
Pine	9.85	10.63
ΔS^1	4.51	5.19
S_r/S^2	1.84	1.95
Alfalfa	7.55	7.99
ΔS	2.36	2.80
S_r/S_f	1.45	1.54

1. Change in S compared to fallow soil.
2. S_r = S(rooted), S_f = S(fallow).

than herbaceous plants in stabilizing soil against landslides. Because of their potential large diameter and length, tree roots are especially significant in soil reinforcement, and thus slope stability.

Earlier studies of slope stability have usually been by observation in uncontrolled and uncontrollable conditions. Thus, the work of Waldron and his colleagues points the way to experimentation and manipulation of some of the factors affecting slope stability that should lead to a better understanding of the processes involved.

3. Water use by trees

Reports are continuing to illustrate the ability of trees to obtain water from great depths, far beyond the lower boundary of the soil profile (e.g., McColl, 1977; Arkley, 1981). Use of deep moisture is particularly evident in areas of the western U.S. with a pronounced dry summer.

Arkley (1981) studied soil moisture regimes under a mixed conifer forest at 16 sites in the San Bernardino Mountains of southern California for 5 years, and found moisture depletion to depths in excess of 274 cm from coarse-loamy and sandy-skeletal soils and underlying decomposing granite (Fig. 3). The forest not only survived, but was highly productive because of the use of this deep moisture, as summer drought is extremely severe. Precipitation from May 1 through August 31 over 78 years was 25 mm in 44% of the years. Moisture depletion is most rapid from the upper layers of soil early in the season in May and June, but is dominantly from the deeper layers in July and August (Arkley, 1981). Such use of such deep moisture by trees could explain the relatively small runoff measured in southern California streams compared with that estimated by the water-balance method. The use of deep moisture beyond that in the solum presents a difficult problem in assessment, and is one avenue of research that should be pursued.

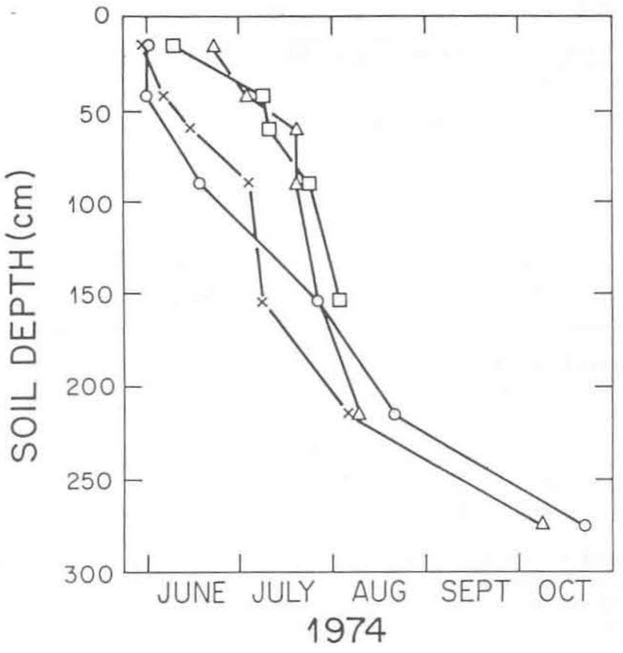

Figure 3.--Increase in depth of dry soil at four sites over summer in mixed conifer forests. California (from Arkley, 1981).

IV. SOIL VARIABILITY, SAMPLING AND TAXONOMY

1. Soil variability and sampling

The extreme variability of forest floor material and mineral soils is a perennial problem in research. Typically, a "reasonable" number of samples is selected from plot areas, and results are expressed as means with associated variances. More recently, attention has been directed to the variability itself and estimation of the number of samples required for adequate representation of various physical and chemical properties (e.g., Lloyd and McKee, 1983; Quesnel and Lavkulich, 1980).

It is important to describe the variability and determine how to deal with it, rather than to ignore it by avoidance or by merely using mean values. Warrick and Nielsen (1980), although not dealing specifically with forest soil variability, addressed these problems. They point out that groupings of soils (e.g., by taxonomic separation) are designed for broad applications, and are based on many factors. Consequently, any specific physical property plays only a minor role, and homogeneous mapping units do not indicate degrees of internal variance. Often, for research or management purposes, we need to know what such variability is, how to describe it, and how to use the information effectively. Warrick and Nielsen (1980) discuss how soil variability can be best expressed, how to determine sample numbers, scaling for data reduction and problem solving, and spatial structure.

Kratochvil and Taylor (1982) point out that the reliability of any analytical measurement depends on sample quality. They discuss the sampling process and its design, the problem of bulking samples, and problems of sample storage, preservation and pretreatment that can make analytical results unreliable and difficult to interpret.

2. Soil taxonomy

There is a critical need to investigate the soil moisture and temperature regimes as predictors of range and forest potentials, especially in the western U.S. The original concepts of "soil climate" designed for soil classification have been incompletely researched and have not been applied consistently over the Western states. The taxonomic class limits for soil climate used to define and delineate natural areas of soil on the landscape do not consistently fit the natural vegetation boundaries, because they were defined for cultivated agricultural crops.

Early soil classification in the United States did not include soil moisture *per se* (Marbut, 1928), and it was not used as a definitive criterion for soil classification in the United States until 1951 (Smith, 1973). Now both soil moisture and temperature regimes are used as criteria in the new "Soil Taxonomy" (Soil Survey Staff, 1975), although problems still exist due to disagreement about ways of estimating these regimes.

Soil moisture regimes of "Soil Taxonomy" are based on the time during the year that the moisture-control section is wet, moist, or dry (Soil Survey Staff, 1975). The moisture-control section is that between the depths of penetration of 2.5 cm and 7.5 cm of water applied to dry, but not air-dry soil. The location of the moisture-control section is critical for determining the soil moisture regime, and its present definition is not good enough. There have been practically no field validations made of the moisture regimes assigned during routine soil mapping.

A new method using commonly-determined soil data for moisture-holding properties has been proposed by Zobeck and Daugherty (1982). This new method avoids many problems that exist under field conditions that make determination of the moisture-control section so difficult.

3. Remote sensing and soil mapping

Spatial data acquired by either aircraft or spacecraft has been used only minimally to stratify landscapes into soil temperature and moisture regimes. Little information exists for correlating land surface characteristics, as recorded by a multispectral scanner, to temperature and moisture regimes measured on the forest floor. Also, relationships between forest canopy reflectance and/or emittance and soil profile temperature and moisture have not been well defined. Previous research has focused on the plant canopy in relation to soil profile properties for cultivated croplands (e.g., Hatfield et al., 1982) and there is little data for forests.

Recent research is now focusing on forested landscapes. For example, DeGloria (1983) used diurnal temperature-difference and temperature-sum data to improve methods for stratifying forested landscapes in northern California into those exhibiting unique plant and soil temperature and moisture regimes, and also those characterizing sites suitable for reforestration or aforestation.

V. SOIL MICROBIAL CHARACTERISTICS

Recent advances in understanding the microbial ecology of forest soils are important, as many critical steps in the cycling of elements in forest ecosystem are microbially-mediated. There has been a healthy shift from population counts and organism identification, to studies of microbial activity and functioning (e.g., Killham et al., 1983, discussed later). Future research requires further refinement of techniques for in situ measurements under conditions of forest systems where characteristics such as deep litter layers, mycorrhizal associations, and tremendous spatial variability, are common. Some recent advances in microbial techniques that may be useful in forest soil research are mentioned below.

1. Techniques

Salonius (1981) described the metabolic capabilities of forest soil microbial populations with reduced species diversity in model systems. The results of this study demonstrated the pitfalls of accepting those members of the soil microbial population which are isolated by traditional methods (e.g., serial dilution method, or soil washing techniques) as representative of the whole soil population.

Jenkinson and Powlson (1976) described a new method for the determination of biomass in soil. Soil is fumigated with $CHCl_3$ vapour, the $CHCl_3$ removed, and the soil is then incubated. The biomass is calculated from the difference between the amounts of CO_2 evolved during incubation by fumigated and unfumigated soil.

Schnurer and Rosswall (1982) described a spectrophotometric determination of the hydrolysis of fluorescein diacetate (FDA) which appears to be a simple, sensitive, and rapid method for determining microbial activity in soil and litter.

A selective inhibition technique to estimate the relative contribution of bacterial and fungal population to soil or litter respiration has been described by Andersons and Domsch (1975). Difficulties which had previously limited the *in situ* use of selective inhibitors such as insufficient inhibitor specificity, inhibitor inactivation or degradation, and measurement errors due to elimination of competitor populations, were either resolved or methodologically avoided in their experiments.

Casida, Klein and Santoro (1964) revised the 2,3,5-triphenyltetrazolium chloride technique of determining soil dehydrogenase activity, to give greater sensitivity and reproducibility, and to allow examination of different soils without first determining their moisture-holding capacity. They showed that tetrazolium reduction at 37°C was biological and was not affected by chemical reduction of the dye which was observed at higher temperatures.

Sundman and Sivela (1978) described a refinement of a simple method (Hansen *et al.*, 1974), for measurement of fungal hyphae in soil, in which homogenized soil dilutions are stained and collected on membrane filters for measurement.

2. Mycorrhizae

Earlier studies of the cycling of nutrients in forest ecosystems examined the nutrients stored in various main components and the rate of movement between these components. The roles of small components, at least in terms of biomass, were ignored or lumped together with those of larger, more obvious components. Such has been the case for mycorrhizae, despite the enormous literature about them, and their wide occurrence in forest soils. Mycorrhizae obviously do not comprise much of the standing biomass in a forest ecosystem, and the tedious, labor-intensive effort required by their study (along with associated tree roots) has postponed attention of their functional aspects until quite recently.

Fogel (1980) estimated that mycorrhizae accounts for about 50% of the annual throughput of biomass (Table 4), and for 43% of the nitrogen released annually in a Douglas-fir ecosystem. These transfers are about 5 times larger than the release from litter fall or litter decomposition. Estimates of biomass or surface area of mycorrhizae are needed before information about ion absorption by mycorrhizae can be applied. Data on mycorrhiza production, senescence and decomposition, of which there are very few published reports, is also required. He emphasizes that our best information is usually derived from data on fine roots (<5 mm diameter), which may or may not include mycorrhizae.

The recent paper by Vogt *et al.* (1982) also highlights the important role of mycorrhizae in nutrient cycling in forests. Although mycorrhizae constituted only about 1% of the standing biomass in two *Abies amabilis* stands studied, they contributed about 14-15% to the net primary production (NPP). Mycorrhizae fungi plus fine tree roots contributed about 45% of NPP in the younger stand, and about 75% in the mature stand. The contributions to nutrient turnover are shown in Table 5. Turnover of nitrogen was twice as great in mycorrhizal fungi reproductive structures alone, compared to turnover by litterfall.

le 4.--Standing and throughput biomass in a young Douglas-fir ecosystem in Oregon (from Fogel, 1980).

Ecosystem component	Standing biomass		Throughput biomass	
	kg ha^{-1}	% of total	kg ha^{-1}	% of total
Total above-ground	258,128	58	2,817	9
Roots	49,289	11	†	†
Mycorrhizae	25,023	6	14,611	50
Forest floor	19,034	4	3,032	10
Fungi	9,885	2	9,214	30
Soil organic matter	87,600	20	†	†

†No data.

Table 5.--Nutrient turnover showing important role of mycorrhizae in Abies amabilis ecosystems, Washington (from Vogt et al., 1982).

Ecosystem and component	N	P	K	Ca	Mg
	kg ha^{-1} yr^{-1}				
23-year-old stand:					
Mycorrhizal fungi reproductive structures	27	4	4	4	1
Conifer roots (≤2 mm), including mycorrhizae	60	10	20	30	10
Litterfall	14	1	2	11	1
180-year-old stand:					
Mycorrhizal fungi reproductive structures	41	7	9	4	2
Conifer roots (≤2mm), including mycorrhizae	110	20	20	30	10
Litterfall	20	3	3	17	3

The authors emphasize, first, that recent nutrient-cycling studies have shown a shift in the zone of intensive rooting from the mineral soil to the detritus with increasing stand age; secondly, that there is a shift in the production balance from above-ground to below-ground structures with stand age. Clearly, both the experimental techniques used, and the functional relationships between mycorrhizal fungi and tree productivity require further research.

3. Nitrogen cycle

Major efforts have been made to increase our understanding of the nitrogen cycle in forested ecosystems. The proceedings of the recent International

Workshop in Sweden represent an excellent review of the subject (Clark and Rosswall, 1981). A prime concern among forest soil scientists is the relationship between soil nitrogen and tree growth, as reviewed by Powers (this volume). Also, Keeney (1980) has provided an excellent review on the prediction of soil nitrogen availability in forest ecosystems.

Denitrification, the major biological processes through which fixed N is returned from soil to atmosphere, has been thoroughly reviewed by Firestone (1982). Denitrification studies in forest, however, are few (e.g., Melillo _et al._, 1982; Strauss, 1983). Estimates of denitrification rates in northern hardwood soils under anaerobic conditions range from 9.0 kg N ha^{-1} yr^{-1} in a 50+ year-old-stand to 51.6 kg N $ha^{-1}yr^{-1}$ in a 2-year-old stand, and under aerobic conditions from 0.4 to 1.4 kg N ha^{-1} yr^{-1}, in the two respective stands (Melillo _et al._, 1982). Strauss (1983) found values <1 kg ha^{-1} yr^{-1} for a mixed conifer forest in the Sierra Nevada, California.

In contrast, studies of fixation of atmospheric N in forest ecosystems have been numerous, primarily through the use of the acetylene reduction assay. However, unless many determinations are made on a regular basis over long periods, there is considerable uncertainty extrapolating from instanteous assays of N_2-fixation to estimation of fixation on an annual or rotation basis. Hardy, Burns and Holsten (1973), provide a comprehensive review of the acetylene reduction method and Gibson and Newton (1981) give an update on the general topic of nitrogen fixation by plants.

The role of both symbiotic and non-symbiotic nitrogen fixation in forest soils has been studied. For example, Lawrie (1981) estimated N-fixation rates in some Australian understory legumes, ranging from 0.004 to 18.8 kg N $ha^{-1}yr^{-1}$. Fixation by nodulated tree species are considerably higher; e.g. Johnsrud (1978) estimated an annual fixation rate of 43 kg ha^{-1} for 30-year-old _Alnus incana_ in Norway. The reported rates of non-symbiotic N-fixation (e.g., Tjepkema, 1979; Vance, Henderson and Blevins, 1983) appear too low to make significant contributions to the soil nitrogen supply.

Studies of N-mineralization in forest soils have also intensified lately, and included rates of production of nitrate and ammonium following various forest management practices (e.g., Edmonds and McColl, 1983) and in forests of different site quality (e.g., Vogt and Edmonds, 1982).

Refined techniques suited for monitoring denitrification, nitrogen fixation and nitrogen mineralization under real field conditions are needed for future research.

Effects of nitrogen inputs from "acid rain" on microbial activity in forest soils are being studied. For example, Killham _et al._ (1983) assayed three soil enzymes (urease, phosphatase and arylsulfatase), which are involved in the catalytic conversions of organic N, P and S to inorganic forms, to determine potential effects on the availability of these nutrients, and to determine the response of individual soil microbial processes. These researchers studied a granitic, Sierra Nevada forest soil planted with ponderosa pine. They also measured soil respiration and dehydrogenase activity to assess generalized effects on microbial activity. Although changes in C-availability occurred in acid-treated soils, changes in N supply appeared to be the major mechanism through which simulated acid rain affected soil microbial activity.

CONCLUSIONS

Many of the recent advances in the collection procedures, analysis, and interpretation of data of forest soils involve modification of methods and techniques originally designed for cultivated agricultural soils. Wider use is needed of modified methods of measuring CEC of forest soils that account for their lower pH compared to agricultural soils. New instrumentation useful for chemical analyses of forest soils includes "Flow Injection Analysis" techniques which improve sensitivity and speed of operation. Disturbance of surface soil by various management practices is a problem receiving much recent attention; studies of soil compaction documenting decreased tree-growth have been published. Recent studies have quantified soil reinforcement by tree roots, which is important to maintenance of slope stability. Water-use from depths below the solum has been measured. Problems related to forest soil variability, mapping, and taxonomy have also been identified. The role of the forest floor continues to receive much attention, and increased research in soil microbiology and in nitrogen cycling exemplify the continuing interest in the important roles that the soil plays in nutrient cycling processes in forested ecosystems.

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